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Closed Vessel examination of Four Series of Cool Propellants

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ARMAMENT RESEARCH ESTABLISHMENT.

MEMO. No.16/49

(Weapons Research Memo. No.5/49)

Closed Vessel examination of Four Series of Cool Propellants.

H.A. Flint.

Summary.

The main object of this investigation was to examine, by Closed Vessel methods, the burning characteristics of four propellants with adiabatic flame temperatures considerably lower than that of any existing Service composition, but manufactured from conventional propellant ingredients.

Each propellant series so examined contained four compositions with flame temperatures of 2450°, 2200°, 1950°, and 1700°K respectively, the upper limit corresponding to cordite N and the lower limit to compositions which, for various reasons, are probably too cool for Service use.

The first series contained picrite as main ingredient, guncotton, carbamite as stabiliser, and diethylene glycol dinitrate (D.G.N) and dibutylphthalate (D.B.P) as coolants. The second series was similar to the first, but with the D.G.N. replaced by D.B.P. with the addition of nitroglycerine (N.G). The third and fourth series contained guncotton as main ingredient, with N.G, D.B.P. and carbamite in the third, and D.G.N, D.B.P, and carbamite in the fourth.

It is concluded that all of these compositions burn normally in the Closed Vessel when they are of such a shape (viz. slotted tube or cord) that there is no gas flow across the propellant burning surface, in which case the rate of burning can be expressed in the form βP^{α}, where P is the pressure at any instant, and β and α are constants for any one composition and charge temperature. For the picrite compositions α was less than unity in each case, and decreased with reduction in propellant flame temperature, but was very nearly unity for all the non-picrite samples. In each series, reduction in propellant flame temperature reduced the rate of burning over the whole pressure range. This effect was most pronounced with the picrite - D.G.N. series, and, in the gun, leads to the need for a reduction in propellant size, for the same ballistics, as propellant flame temperature is reduced. The temperature coefficient of rate of burning was comparatively insensitive to change in propellant flame temperature.

Change in propellant shape, examined in the case of the picrite compositions only, was found to have a marked effect on burning. The change was from the parallel-burning slotted-tube to granular multitube, in which gas-flow tangential to the propellant surface inside the perforations occurs during burning. It is concluded that in some cases, and particularly at low initial temperature of the charge, the velocity of such gas flow was sufficiently high to cause a considerable increase in rate of burning, due to the-called propellant erosion. This phenomenon, together with the difficulty of ensuring a sufficiently high rate of flow of igniter gases into the perforations for efficient ignition, leads, in most cases, to a

complicated relationship between rate of burning and pressure which could not be reduced to a form suitable for use in internal ballistic equations. The relationship became increasingly complex as the propellant flame temperature was reduced, and also as the charge temperature of any one composition was reduced. In general, the broad conclusions regarding the dependence of erosive burning on the propellant flame temperature which may be drawn from the results of these firings are in agreement with theory.

The general conclusion is that, on grounds of accuracy of ballistic prediction and efficiency of ignition, the granular perforated propellant shape is inferior to slotted-tube.

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C O N T E N T S.

1. Introduction.

Towards the end of World War II, it became clear that, for successful future development of high-perforance automatic guns, (for the A.A. role, in particular), some solution to the gun-wear problem was essential. Experience during the war had shown that in single shot firing, and at slow rates of automatic fire, gun life could be considerably extended by using cooler propellants. The development of propellant compositions cooler than any then in Service use appeared therefore to offer at least a partial solution to the problem of designing high-performance guns which would have a reasonably useful life.

There was in existence at that time an Armament Research Department Committee known as Propellants Research Panel B, the function of which was to co-ordinate problems of the performance of propellants used at high pressures in relation to their manufacture and their chemical, physical and mechanical properties. At that date, the present Explosives Research and Development Establishment had not yet been formed, and its personnel was included in the A.R.D. The membership of the above Panel was made up of Chemists, Ballisticians, and Service Representatives. Towards the end of 1945, the Panel considered the question of developing cool, less erosive propellants for guns, and proceeded to appoint, from among its membership, a sub-committee (called the sub-committee for Research on Cool Propellants for Guns) to deal with this problem. The terms of reference of the sub-committee included:-

(a) The planning of the investigation.

(b) The ordering of the necessary stores.

and (c) The progressing of the work.

At the first meeting of the sub-committee, held on 8th October, 1945, it was decided to examine a series of four propellant compositions, based on Service materials and diethylene glycol dinitrate (i.e.D.G.N) and having adiabatic flame temperatures(T_o) of 1700, 1950, 2200 and 2450°K respectively. These compositions were designated Series I Cool Propellants, and small samples were manufactured by the Propellants Branch for Closed Vessel examination. In formulating these compositions, the Propellants Branch were requested to bear in mind the question of flash and the necessity for a high nitrogen content in the products of combustion.

The following is an extract from the report by the Propellants Branch on design and manufacturing aspects of these four compositions:-

"The ingredients for this series of propellants were chosen from Service materials and Diethylene Glycol Dinitrate (D.G.N); the latter ingredient was chosen because it is more suited than Nitroglycerine for use in cool and ultra-cool propellants on account of its lower calorimetric value (Cal.Val.), and there is also every reason to believe that in a reasonable period of time it will be available for large-scale manufacturing trials. The propellant shapes requested for Closed Vessel examination (multitube and slotted-tube) necessarily implied manufacture by the solvent process, and it was accordingly decided to base the compositions on the following ingredients:-

Picrite
Guncotton
D.G.N.
Dibutyl Phthalate (D.B.P)
Carbamite

"The method of formulating the compositions was as follows:-

(i) All the compositions contain 60% Picrite and 20% guncotton; by this means the optimum guncotton/liquid ratio is combined with a favourable proportion of crystallines, thus assisting in the production of compositions with satisfactory manufacturing and physical characteristics and yielding a high proportion of nitrogen in the products of decomposition.

(ii) All the compositions are based on a reasonably low carbamite content and dibutyl phthalate is employed as a liquid coolant. The proportions of carbamite alone neccessary to formulate the cooler compositions would be liable to lead to manufacturing difficulties arising from the formation of the picrite - carbamite complex and an abnormally high content of crystallines.

(iii)The hottest composition (T_o=2450°K) contains no dibutyl phthalate; i.e. the proportions of D.G.N. and carbamite are adjusted to give the required flame temperature.

(iv) The three cooler compositions are then obtained by the replacement of D.G.N. by dibutyl phthalate, keeping the proportion of carbamite as in the hottest composition.

"The solvent chosen for this manufacture - Acetone/Alcohol 60/40 parts by weight - is that normally employed in A.R.D. for compositions of this type in which the liquid constituent (in this case D.G.N. + D.B.P) is a good gelatiniser for nitrocellulose, since the processing properties are then somewhat superior to those obtained with the more conventional Acetone/Water solvents. It is likely, however, that should compositions of this type ever reach bulk production stage, it would be desired to employ Acetone/Water solvents wherever possible, Accordingly, duplicate batches of the two extreme compositions F.487/44 and F.487/47, have been prepared using Acetone/Water 90/10 parts by weight as solvent in order to assess any difference in burning properties resulting from a change of solvent".

At the time this investigation was initiated, D.G.N. was available as an ingredient for gun propellants in quantities sufficient only for experimental work, and it was considered that a supply which would be adequate for Service compositions would be difficult to arrange. On the other hand, D.B.P. was in fairly good supply, which could be increased if necessary. Accordingly, a second series of propellant compositions similar to the first, was designed, the difference being that, instead of D.G.N, suitable proportions of D.B.P. and N.G. were employed to adjust the adiabatic flame temperatures to the original values, viz. 2450, 2200, 1950 and 1700°K respectively; the proportions of picrite, nitrocellulose and carbamite were kept the same. Small samples of this second series, designated series I.A. Cool Propellants, were manufactured by the Propellant Branch, in both slotted tube and multitube shapes, for Closed Vessel Examination.

In view of possible difficulties in the future supply of picrite, it was decided to investigate a third series of compositions, of the same flame temperatures as the previous series, but manufactured from ingredients other than picrite. Nitrocellulose was chosen as the main constituent: the series I.B. Cool Propellants contained 65% of this ingredient, and 2% carbamite, the proportions of the remaining ingredients, N.G. and D.B.P. being adjusted to give the required flame temperatures.

In series I.C. the percentage of guncotton was increased to 70, but the same carbamite content of 2% was used. The remaining ingredients were D.G.N. and D.B.P, and their proportions were adjusted to give the same four flame temperature levels as before.

/Samples

Samples of Series I.B. and I.C. Cool Propellants in cord form, were manufactured by the Propellants Branch (which now forms part of the Explosives Research and Development Establishment) for Closed Vessel testing.

The compositions and dimensions of the above four propellant series, together with calculated data, are tabulated in Appendix A.

2. Object of the investigation.

In general, the object of the investigation was to examine, by Closed Vessel methods, the burning characteristics of propellants with adiabatic flame temperatures considerably lower than that of any propellant at present in Service use.

In particular, with Series I Cool Propellants the objects were to:-

(a) Examine the burning characteristics at various flame temperature levels, of propellants containing picrite as main ingredient and D.G.N. as a subsidiary ingredient.

(b) Study the effect of initial temperature on the burning of such propellants.

(c) Study the effect of shape on the burning.

(d) Study the effect of change in processing solvent on the burning.

(e) Compare the experimentally - determined force constants for the propellants with the calculated values.

The object of firing the Series I.A. compositions was to examine the effects, in connection with (a), (b), (c) and (d) above, of substituting N.G. and D.B.P. for the D.G.N. in the Series I. compositions without altering the flame temperatures,

With the Series I.B. compositions the object was to study the characteristics, as at (a) and (c) above, of a series of compositions having the same flame temperatures as those of Series I. but with guncotton as main ingredient and N.G. and D.B.P. as secondary ingredients.

The object of Series I.C. was to examine the effect, under (a) and (c), of substituting D.G.N. for the N.G. and some of the D.B.P. in Series I.B. compositions, and slightly increasing the guncotton content, without altering the flame temperatures.

3. Method.

The firings were carried out in the standard design of Closed Vessel used for routine investigations, which has a chamber capacity of 700 cc.

For Series I. and I.A. Piezo-Electric pressure-time recording was employed, but the newly-installed apparatus for recording rate of pressure rise (i.e. $\frac{dP}{dt}$) against pressure (P) was used.

In the case of Series I, three rounds of each sample were fired, at a loading density of 0.2 grams per cc. (i.e. at a charge weight of 140 grams) at charge temperatures of 35°F and 120°F. Similar firings were carried out with the Series I.A. compositions, the only difference being that, with the 1950° and 1700°K samples the loading density was increased to 0.25 grams per cc. in order to increase the maximum pressure.

The main object in firing at two charge temperatures was to examine

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the effect of shape on temperature coefficient, as samples were provided in both slotted-tube and multitube form, but Series I.B. and I.C. were supplied in cord form only. As the rate of burning temperature coefficients of these two series, in cord form, were not likely to differ greatly from those for the slotted-tube form of Series I. and I.A, they were fired at the standard temperature of 80°F only. In these two cases, three rounds of each sample were fired, at loading densities of 0.2 grams per cc. for the 2450° and 2200°K compositions, and 0.25 grams per cc. for the 1950° and 1700°K compositions.

Final results were calculated from the mean results of the three-round series. In each case, the burning law was derived in the form:-

Rate of burning = βP^{α},

where P is the pressure and β and α are constants for any particular sample and charge temperature. The use of an index burning-law in internal ballistic theory leads to considerable complication, and it is preferable to reduce it to the equivalent linear form, $\beta_1 P_0$: β_1 is sensitive, to some extent, to the maximum gun-pressure, and in the present instance the maximum true gun-pressure was taken to be 24 tons per sq.in. (i.e. 20 tons per sq.in. "copper" pressure). Also, in the Closed Vessel β is sensitive to loading-density. Pike (1) has shown that the Closed Vessel loading-density should be such that the maximum pressure is equal to that at all-burnt in the gun; as an approximation, this can be taken as being 75% of the maximum gun-pressure, or 18 tons per sq.in. in the present case. Thus, if the Closed Vessel maximum pressure differs from this figure, it is necessary to make an appropriate correction to the derived value of β . It is customary to denote the corrected constant in the linear burning law by the symbol $\beta_{1(24)}$.

Pike (1) has also shown that the correct value of force-constant (λ_1) to use in R.D.38 internal ballistic theory (which employs the fictitious co-volume= the reciprocal of the propellant density) is that corresponding to the pressure at all-burnt in the gun (assumed to be 18 tons per sq.in. in the present instance). This force constant is denoted by $\lambda_{1(18)}$.

Values of $\beta_{1(24)}$ and $\lambda_{1(18)}$ were calculated for each set of firings. Also, values of λ_0 were deduced from the experimental results for comparison with the figures calculated from the nominal compositions and thermochemical data.

In the case of the slotted-tube samples, temperature coefficients of burning rate were calculated from the constants $\beta_{1(24)}$ and $\lambda_{1(18)}$. It was not possible to use this method for the multitube samples, for which, in most cases, it was not possible to deduce simple burning laws. In such cases, temperature coefficients were calculated by a previously reported method, in which time intervals, at the two charge temperatures, for equal increments in pressure, are compared.

4. Results.

The Closed Vessel results are summarised in Tables I to IV.

In most cases the burning of the multitube samples was abnormal, and it was not possible to obtain a simple relationship between rate of burning and pressure. In such cases, therefore, it was not possible to deduce values for $\beta_{1(24)}$.

In these cases in which two shapes of the same composition were provided, the figures for $\lambda_{1(18)}$ are the mean for the two shapes.

In the present instance, "temperature coefficient" of burning rate is defined as being the increase in quickness when the charge temperature is raised from 35° to 120°F, quickness being the ratio $\lambda\beta/D$, where λ and β are, respectively, the force and rate of burning constants, as before, and D is the smallest dimension of the propellant.

λ_1 and λ_0 are in units of tons per sq.in./grams per cc. and $\beta_1(24)$ is expressed in inches per sec./tons per sq.in.

α is the index in the law:- Rate of burning $= \beta P^{\alpha}$.

Closed Vessel Firing Results.

Table I. Series. I. Cool Propellants.

Composition No.	Lot No.	Solvent	α	$\lambda_1(18)$	λ_∞ Experimental	λ_∞ Calcd.	SLOTTED TUBE $\beta_1(24)$ at 80°F	SLOTTED TUBE Temp. Coeff. %	MULTITUBE Temp. Coeff. %
F487/44	ARD2079		0.835	70.6	63.6	62.5	0.590	14	5
F487/45	ARD2080	Acetone/	0.814	65.4	58.0	58.0	0.473	14	3
F487/46	ARD2081	Alcohol	0.764	61.8	54.0	53.3	0.393	17	0
F487/47	ARD2082		0.667	55.6	47.3	47.6	0.303	19	19
F487/44	ARD2092	Acetone/	0.842	71.4	64.4	62.5	0.584	13	6
F487/47	ARD2093	Water	0.795	54.7	46.5	47.6	0.329	16	18

Table II. Series I.A. Cool Propellants.

Composition No.	Lot No.	α	$\lambda_1(18)$	λ_0 Experimental	λ_0 Calcd.	SLOTTED TUBE $\beta_1(24)$ at 80°F.	SLOTTED TUBE Temp. Coeff. %	MULTITUBE. Temp. Coeff. %
F527/153	ARD2408	0.801	70.6	63.5	62.2	0.554	13	6
F527/154	ARD2409	0.770	65.4	57.9	57.9	0.484	10	4
F527/155	ARD2410	0.775	60.8	52.9	52.9	0.405	12	7
F527/156	ARD2411	0.765	55.0	47.7	47.9	0.376	14	6

Table III. Series I.B. Cool Propellants.

Composition No.	Lot No.	α	$\lambda_1(18)$	λ_0 Experimental	λ_0 Calculated	$\beta_1(24)$ at 80°F.
F428/178	ARD2460	0.983	69.3	62.7	61.2	0.639
F428/179	ARD2461	0.982	64.1	57.3	57.0	0.542
F428/180	ARD2462	1.009	60.3	52.9	52.0	0.467
F428/181	ARD2463	1.042	56.9	49.3	47.1	0.408

Table IV. Series I.C. Cool Propellants.

Composition No.	Lot No.	α	$\lambda_1(18)$	λ_0 Experimental	λ_0 Calculated	$\beta_1(24)$ at 80°F.
F487/66	CRDD2604	0.950	68.0	61.5	61.4	0.666
F487/67	CRDD2605	0.951	63.8	57.0	57.2	0.559
F487/68	CRDD2606	1.008	60.4	53.4	52.3	0.476
F487/69	CRDD2607	1.003	56.7	49.2	47.5	0.418

5. Discussion of results.

(a) Series I. Compositions.

Figure 1, in which rate of burning is plotted against pressure, shows that all the slotted tube samples burned in a normal manner at both charge temperatures. These curves also indicate that the use of Acetone/Water solvent in place of Acetone/Alcohol had little effect on the burning of compositions F.487/44 and 47. The greater difference in this respect was with the coolest composition, as indicated by the values of $\beta_1(24)$, the change in solvent causing a difference of some 8%. This is not readily apparent from the plotted rate of burning curves, which have to be extrapolated for $\beta_1(24)$ to be deduced. Such extrapolation is, of course, undesirable, and it was for this reason that, in subsequent firings of very cool compositions, the loading density was increased from 0.2 to 0.25 grams per cc.

The values of $\beta_1(24)$, for the slotted-tube shape of propellant, and a charge temperature of 80°F, are plotted against adiabatic flame temperature in Fig.9. This curve shows that the relationship between $\beta_1(24)$ and flame temperature is very nearly linear.

Table I. shows that the temperature coefficient of the slotted-tube shape tends to increase as the adiabatic flame temperature is reduced. The actual figures call for little comment, being representative of the N-type of propellant. Three of the multitube samples, however, had temperature coefficients which were very low (zero in one case), but the remaining multitube sample (the coolest composition) had the same temperature coefficient as the corresponding slotted-tube sample.

In the two cases examined, the use of Acetone/Water solvent in place of Acetone/Alcohol had no significant effect on the temperature coefficient of either the slotted tube or the multitube samples.

It has previously been stated that, in most cases, the burning of the multitube samples was so abnormal that it was not possible to deduce simple burning laws, and that, in such cases, it was necessary to resort to a comparison of time intervals to determine temperature coefficients. In the present instance, this method may not give a reliable indication of the performence of the propellant in the gun. Basically, the reason for this lies in the difference in loading density between the gun and the Closed Vessel and the erosive burning which occurs in the perforations, during the early stages of burning.

It is well known that turbulent flow of propellant gases tangential to the propellant burning surface can considerably enhance the rate of burning by increasing the conduction of heat back to the propellant surface. This increased burning is additional to any mechanical removal of propellant from the burning surf ce due to the friction of the fast-moving gases. These two phenomena are frequently referred to jointly as erosive burning, although it is of course, an accurate description of only the second of these two phenomena.

The gases produced by combustion inside the perforations of the multitube shape of propellant are accelerated until they emerge from the grain, and, in certain circumstances, may acquire considerable velocity tangential to the propellant burning surface. Erosive burning, therefore, may occur in propellants of this shape. The slotted-tube shape, however, may be considered to be free from erosive burning, in the Closed Vessel, as the gases formed inside the perforations are free to come out through the slot, and the conditions are such that any velocity tangential to the burning surface can be of only a very low order. In the case of the

/slotted-

slotted-tube shape, therefore, burning may be assumed to be pressure-dependent only, and to proceed by parallel layers. This is, no doubt, an over-simplification of the mode of burning, but it provides a means of examining whether, in any particular cases, there is any appreciable erosive burning,

In the present instance, we have two sets of samples, pressed from the same mixture of ingredients, one in slotted-tube form and the other multitubular. If, at any pressure, the rate of burning of the M.T. sample is appreciably greater than that of the S.T. sample of the same composition, then the suspicion arises that the excess may be due to erosive burning. Thus, in Fig.3, in which the ratio(Rate of burning of M.T.)/(Rate of burning of S.T.) is plotted against the amount of charge burnt (i.e. a measure of the pressure) for each of the four compositions and each of the two charge temperatures, the shapes of the curves suggest that, in most of these cases, there was some erosive burning.

It should be mentioned that in calculating rates of burning for the M.T. samples, the geometrical form function was used, assuming parallel-layer burning of the propellant. As the accuracy of such assumptions depends upon the absence of erosive burning, then if erosive burning does, in fact, occur the calculated figures are not true rates of burning but apparent rates.

Before attempting an explanation of Fig.3, it is necessary to consider ignition phenomena, and theories of erosive burning. It is well known that, qualitatively, hot propellants are more readily ignited than cool compositions. In the present experiments, the same ignition system was used for all compositions, and its "efficiency" may have decreased with reduction in propellant flame temperature. The complete mechanism of propellant ignition is not fully understood, but there is little doubt that in certain circumstances, the charge, is, to some extent, self-igniting, i.e. the igniter ignites part of the charge, and the propellant gases assist in igniting the remainder. Closed Vessel experience suggests that the corners of a stick of propellant are more readily ignited than the surfaces, as, on those occasions in which the charge has failed to burn in spite of the igniter having functioned, some burning at the corners of the sticks of propellant has frequently been observed. In particular, in a recent series of Closed Vessel firings of a cool propellant (D.B.P.560.), the reduction in stick length from 5 ins. to 1 in., in steps of 1-in, had a marked effect on the very early stages of burning, with a progressive improvement in ignition. At the sharp corners of a propellant stick, the heat input during ignition is in two directions and the propellant temperature increases more rapidly at this point than over the remainder of the propellant surface. It seems reasonable to suppose, therefore, that ignition commences at the stick corners, and then spreads over the remainder of the surface.

The "corner-burning" effect is an additional complication in the comparison attempted in Fig.3, as the fired length of the slotted-tube was 5-ins., and the multitube was, of course, chopped to a much shorter length (about 0.6 to 0.65-in.). This would tend to favour the ignition of the multitube. If the rate of burning curves for the slotted-tube shape in Fig.1.are extrapolated back in the direction of the origin, it is found that in nearly every case the curve intersects the pressure axis at zero rate of burning. In general, the intercept tends to increase as the propellant adiabatic flame temperature is reduced, or as the charge temperature is reduced. This points to non-uniform ignition over the charge surface. This effect is less marked with the multitube shape, (presumably because of the corner-burning effect), as can be seen from Fig. 2. In this case, the hottest composition, F.487/44, appears to be the worst offender in this respect, but the burning curves for the

/remaining

remaining compositions, when extrapolated, pass through, or very near, the origin. (In the experimental technique used in this propellant series, the early part of the rate of burning curve is lost in the differentiation of the pressure-time curve). Thus, in some cases the multitube sample appears to burn considerably faster than the slotted-tube, as can be seen in Fig.3.

As burning proceeds, at a faster rate initially at the corners than elsewhere, the corners become rounded off and the "corner-burning" effect dies away. At this stage, the multitube is apparently slower-burning than the slotted-tube, due, it is suggested, to incompletion of ignition in the perforations. The conditions for ignition are much less favourable inside the multitubular propellant grain than outside. The outer surface can draw upon the heat energy of a comparatively large amount of igniter, but the amount of hot igniter gases available to the inner surface is limited, as it has to be forced into the perforation. In this connection, the perforation diameter is important, as it has a bearing on the amount of heat available per unit area to be ignited. Thus, for a perforation filled instantaneously with igniter gases of a certain heat content per unit volume, the total heat available for ignition varies as D^2, where D is the perforation diameter. The area to be ignited varies as D and the heat available per unit surface must therefore be proportional to D also. Thus, the time lag in igniting down the perforation increases as D is reduced. In the present series, the perforation diameters of the four samples were very nearly equal, as were the cut lengths.

The propellant itself probably plays a large part in ignition down the perforation, the flame creeping along the propellant surface, from both ends. By the time internal ignition is completed, the perforations have probably become slightly conical in shape. Before this stage is reached, the gases generated inside the perforations acquire considerable velocity in their efforts to emerge from the grain, and in some circumstances this velocity may be sufficiently high to cause erosive burning. In the present series, in three of the four cases the gas velocity was sufficiently high to cause a very considerable amount of erosive burning at a charge temperature of 35°F, and some erosive burning in other cases also.

In a mathematical treatment of the effect of gas flow tangential to the burning surface of a propellant, Lennard-Jones and Corner (2) concluded that "turbulent" burning is a function of the thickness of the reaction zone of the propellant, and the velocity of the gases tangential to the propellant surface. As the pressure increases, the reaction zone decreases in thickness, and erosive burning would be expected to decrease also if the gas velocity remained unaltered. Somewhat surprisingly, however, the gas velocity in the perforation of a multitubular (or any other) grain decreases as the pressure rises. The propellant rate of burning increases almost linearly with pressure, but the gas density increases also, and the volume of gas generated in unit time, per unit burning surface, remains nearly constant. As the perforation diameter D increases the gas velocity actually decreases, as the volume of gas produced in the perforation varies as D and the area of the hole varies as D^2. Thus, the velocity of flow varies as 1/D, very nearly. Thus, if the whole of the internal surface could be ignited instantaneously at the same time as the external surface, the conditions for erosive burning would be at their most severe, as the gas flow would be at the maximum velocity and the thickness of the combustion zone would be at its maximum also. In practice, it is not possible to achieve this ideal ignition, and the maximum gas velocity, at the ends of the grain, increases as ignition proceeds along the perforation. In some circumstances, the gas velocity can become sufficiently high for erosive burning to occur before ignition in the perforation is completed. Thus, in Fig.3, in those cases in which the M.T. burns faster than the S.T. over part of the burning range, there is probably some erosive

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burning of the M.T. even before the ratio of the burning rates (R) reaches unity. In these cases, it seems likely that ignition in the perforation is completed at or about the maximum value of R.

Charge temperature appears to have a marked effect on erosive burning. It was thought, at one time, that a possible explanation of this might be that the law of erosive burning is dependent upon charge temperature. In order to test this theory, the erosive burning of cordite N under known conditions of gas flow was examined, using a low-pressure interrupted-burning technique, at charge temperatures of -5°, 60° and 140°F. Certain technical difficulties were encountered during these experiments, but the broad conclusion that there was no appreciable change in the erosion rates with temperature may be expressed with some confidence. The actual figures, expressed as ratios of rates of burning with and without erosive burning, were 2.60, 2.58 and 2.55 for charge temperatures of -5°, 60° and 140°F. respectively. It is therefore concluded that the increased erosive burning at low temperature, in the present instance, is not due to any temperature dependence of the erosive burning law. An alternative explanation is that, with reduction in charge temperature, ignition becomes more difficult, and ignition down the perforation after ignition of the external surface becomes longer delayed. In effect, as the charge temperature is reduced, ignition in the perforation is completed at a progressively higher pressure, and this leads to the maximum rate of gas flow, and erosive burning, occurring at a higher pressure also. In other words, in the early stages of burning, at the same pressure level the perforation diameter is smaller with a cool charge than with a warm charge, and this so influences the gas flow in the perforation that there is increased erosive burning as the charge is cooled.

The above phenomenon may have some bearing on the ignition of perforated cool propellants in guns. By adjustment of the quantity and position of the igniting material, it should be possible to accelerate or delay ignition in the perforations. Following from Closed Vessel experience, a long delay would be expected to cause a large amount of erosive burning. A heavy igniter would produce an effect similar to this, as it would raise the pressure at which ignition in the perforation is completed. Erosive burning, of course, causes the perforation diameter to increase at an abnormally high rate, and could result in an increased charge burning-surface, with a consequent increase in maximum pressure and muzzle velocity. With a very gentle igniter, the converse would hold; ignition in the perforations would be completed at an earlier stage, the conditions would approach those of normal pressure-dependent burning, and the ballistics would be lower than in the previous case. In practice it is found that a comparatively weak igniter does, in fact, give smoothest ignition and minimum ballistics, and the ballistic increase and pressure waves become more severe if the amount of igniter is increased. It is possible, therefore, that erosive burning may be one of the many factors which contribute to the difficulty of obtaining satisfactory ignition of perforated cool propellants in the gun; if this is true, the Closed Vessel may be of some assistance in this respect.

Fig.3. shows very clearly that at low charge-temperature, the maximum rate of erosive burning occurs at a progressively higher pressure as the propellant flame temperature is reduced. This is to be expected, from the supposition that the propellant becomes increasingly difficult to ignite, with a corresponding increase in ignition delay. In the case of the coolest composition, it is presumed that the rate of burning is so small and the ignition delay so great that the gas flow in the perforation does not become turbulent and there is little erosive burning. During the process of internal ignition the perforation becomes tapered outwards in longitudinal cross-section, and this, of course, influences the rate of flow.

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In view of the above results, it was decided to use the S.T. shape in preference to M.T. for early trials of cool propellants in guns.

Series I.A. Compositions.

In Fig.4, the rates of burning of the S.T. samples are plotted against pressure, for the two charge temperatures of 35°F and 120°F. The curves are of normal shape, and do not disclose any peculiarities of burning. The values of $\beta_1(24)$ for these compositions (for a charge temperature of 80°F) were less sensitive to propellant flame temperature than were those of Series I, as is shown in Fig.9. In particular, $\beta_1(24)$ for the coolest composition was considerably greater than that of the corresponding Series I. composition. The reverse was true at the highest level of flame temperature, with the result that the decrease in $\beta_1(24)$ from the hottest to the coolest compositions was much less than in the previous series.

The temperature coefficients of all four samples in S.T. form were of the same order of magnitude, and rather lower than those of Series I.

The experimental values of λ_o were in good agreement with the calculated figures.

As in Series I, the M.T. samples burned abnormally in some instances, particularly at low charge-temperature, as shown in Fig.5.

The erosive burning of the M.T. samples was examined, as before, by plotting the ratio (Rate of burning of M.T. sample) / (Rate of burning of S.T. sample) against the amount of charge burnt, as in Fig.6.

In general, the two sets of curves (Fig.3 and 6) display very similar characteristics. The chief difference is that, with Series I.A, there is greater emphasis on the "corner-burning" effect, but there is the same enhanced erosion at low charge-temperature, the same increased delay in internal ignition as the charge temperature is reduced, and the same increased delay in reaching the maximum rate of erosive burning.

Within the limits of experimental accuracy, the temperature coefficients of the M.T. samples were equal, and were only about one-half those of the S.T. samples.

Series I B Compositions

In calculating λ_0 and T_0 for this series and series I.C, improved thermochemical data was used. This had the effect of increasing, both T_0 and λ_0 by about 1 %, in comparison with the previous data.

The rate of burning curves are shown in Fig 7. For this series, and also for series I.C., the new recording apparatus was employed. Comparison of Figs 1 and 7 shows that the change in method of recording, from pressure-time to $\frac{dP}{dt}$ - pressure, has led to a considerable smoothing of the rate of burning curves.

Values of $\beta_1(24)$, for a charge temperature of 80°F, are plotted in Fig. 9, from which it is seen that the present non-picrite compositions are appreciably faster-burning than the corresponding samples containing picrite (Series I and I A). This is not unexpected, as it is known that, in the case of cordite N, for example, picrite size has a considerable effect on rate of burning. The index α in the burning law may be as low as 0.85 if very coarse picrite is used, but tends to approach the normal figure of approximately 1.0 for the hotter colloidal propellants as the picrite is made increasingly finer. In the present instance, the values of α for the series I.B compositions (i.e. non-picrite) were all close to 1.0. On the other hand, the α's for the series I and I.A compositions (i.e. picrite) varied between 0.67 and 0.83.

In three of the four cases, the experimental λ_0 was in good agreement with the calculated value. The experimental λ_0 for the coolest composition, however, was some 4% greater than the calculated figure.

Series I.C. Compositions.

The rate of burning curves shown in Fig. 8 indicate no abnormalities of burning, and are very similar to those for series I.B. From Fig. 9 it is seen that the values of $\beta_1(24)$ for the series I.C. compositions are not very different from those of series I.B. In no case is the difference any greater than lot to lot differences of the same nominal composition. As with the other non-picrite series (I.B), the values of α were very nearly unity, and in this case also there was a slight tendency for α to increase as the propellant flame temperature was reduced.

Here again, the calculated λ_0's were in good agreement with the experimental values except in the case of the coolest composition, where the difference was nearly 4 %, the experimental value being the greater, as before.

Conclusions

(1) In all four series of propellant compositions examined, reduction in adiabatic flame temperature, over the range from 2450° to 1700°K, does not introduce any abnormality in burning, provided that the propellant is of such a shape that high-velocity gas flow tangential to the propellant surface does not occur during burning; in these same circumstances, reduction in charge temperature produced no abnormal effects with the picrite compositions, and there is no reason to suppose that the non-picrite propellants would not burn normally at low temperature also, although they were not examined in this respect.

(2) In all four series, the rate of burning constant, $\beta_1(24)$ decreased with reduction in propellant flame temperature when burning was by parallel layers (i.e. in either S.T. or cord form). The picrite - D.G.N. series was the most sensitive in this respect, $\beta_1(24)$ decreasing, on an average, by about 20% for a reduction in flame temperature of 250°K.

(3) The use of N.G. + D.B.P (series I.A) in place of D.G.N (Series I) reduced $\beta_1(24)$ at the 2450°K flame temperature level, and increased $\beta_1(24)$ at the 1700°K level.

4. All the compositions of the non-picrite series containing D.G.N. (i.e. series I.C.) burned appreciably faster than the corresponding picrite compositions (Series I), this difference increasing with reduction in propellant flame temperature .

5. The substitution of N.G. + D.B.P. (series I.B.) for D.G.N. (series I.C.) in the non-picrite series produced a slight reduction in $\beta_1(24)$, of the order of 2 or 3%.

6. The temperature coefficients of rate of burning for the two picrite series in S.T. form were of the normal order of magnitude; in the D.G.N. series there was a slight upward trend as the flame temperature was reduced, but in the second series the temperature coefficients of the four compositions were equal, within the accuracy of the experimental method.

7. The use of Acetone/Water in place of Acetone/Alcohol as processing solvent had no appreciable effect on the burning of the S.T. form of the hottest composition of the picrite → D.G.N. series either at high or low charge temperature. In the case of the coolest composition of this series, however the above substitution increased $\beta_1(24)$ at 80°F charge temperatures by nearly 9%, and slightly reduced the rate of burning temperature coefficient.

The above conclusions refer specifically to those propellant shapes which burn by parallel layers in the closed vessel, viz. S.T. and cord. The following remarks refer to the multitubular shape; only the two picrite series of propellants were supplied in this shape.

8. In most cases, and particularly at low charge temperature, the relationship between rate of burning and pressure for the M.T. samples of the series I and I A compositions was too complicated for it to be expressed in terms of a simple index law, and values of $\beta_1(24)$ could not, therefore be deduced.

9. At the same charge temperature, the M.T. samples were, in general, faster burning than the corresponding S.T. samples.

10. The temperature coefficients for three of the picrite - D.G.N. compositions of M.T. shape were very low, zero in one case, but in the remaining case, that of the coolest composition, the temperature coefficient for the M.T. was the same as for the S.T. On the other hand, the temperature coefficient for the four picrite - N.G. - D.B.P compositions of M.T. shape were nearly equal, and were about one half of those for the corresponding S.T. samples.

11. The use of Acetone/Water in place of Acetone/Alcohol as processing solvent during the manufacture of the M.T. shapes of the hottest and coolest picrite - D.G.N. compositions had the effect of slightly reducing the rate of burning at both high and low charge temperature, without affecting the temperature coefficient.

12. In the ignition stage, departure from the assumed parallel-layer burning at the corners of the propellant granules had an appreciable effect on the apparent rate of burning of the M.T. samples, in comparison with the S.T. samples which were, of course, fired in considerably longer stick lengths.

13. Ignition in the perforations of the M.T. samples was not completed until an appreciable fraction of the charge had been consumed.

14. The ignition delay referred to in (13) above increased as the propellant flame temperature was reduced.

15. The ignition delay referred to in (13) above increased as the charge temperature was reduced.

(16) At the lower charge temperature, and, in some cases, at the higher charge temperature also, the gas velocity in the perforations of the M.T. samples was sufficiently high to cause erosive burning of the propellant to occur.

17. The erosive burning referred to in (16) above reached its maximum value at a progressively later stage of burning as the propellant flame temperature was reduced.

18. The erosive burning referred to in (16) above reached its maximum value at a later stage of burning when the initial temperature of the charge was reduced.

19. After reaching a maximum value, erosive burning gradually diminished as burning proceeded, due mainly, it is though, to the decrease in velocity resulting from the increasing perforation diameter.

20. Erosive burning was more pronounced at low temperature than at high temperature, with the result that by the particular method of assessment employed, the temperature coefficient for the M.T. shape in most cases appeared to be lower than that of the same composition in S.T. form.

6. Further Work

Further evidence of erosive burning of a perforated propellant shape, in this case tube, has since been obtained with non-picrite propellants of 1950°K flame temperature, series I.B and I.C. In each case two propellant sizes were examined, and the results are discussed in Appendix B.

It is possible that erosive burning, and the lag in completing ignition of the interior burning surface, are factors which contribute to the difficulties of satisfactorily igniting charges of cool granular propellants in the gun. The suggestion here is that if the rate of burning is a discontinuous function of the pressure, this may serve to accentuate any disturbing factors which may already be present.

In Appendix B, it is shown that, in some circumstances, the effect of erosive burning on the burning law approximates to a change in form function θ i.e. if we have the same propellant composition in two shapes, one of which burns in parallel layers and the other burns erosively, then we can use the same law of burning for both by using a fictitious θ for the erosively- burning shape.

In view of the importance of cool propellants for the extension of gun life, and the well-known advantages of the multitubular shape particularly in its application to cool compositions when it is necessary to fill necked cartridge cases to a high loading-density, further investigation of erosive burning is highly desirable on two main grounds, viz:-
(a) its effect on the gun ignition problem, and
(b) its effect on the law of propellant burning.

Much work is now being carried out on propellants of the 1950°K flame temperature level, at which level the picrite composition appears to be much less erosive than the non-picrite types. Lack of sufficient supplies of D.G.N. appears to rule out the use of this material as a propellant coolant, in the immediate future, leaving the alternative of D.B.P + additional N.G. It has therefore been decided to explore the erosive burning characteristics of the series I.A. composition F.527/155, containing 60% picrite, 20% guncotton, 8.86% N.G. 8.50% D.B.P. and 2.64% carbamite.

Samples of this composition have been made by E.R.D.E on the small-scale plant at Woolwich, as follows:- (a) slotted tube (b) cord (c) four samples of multitube, all of the same web size and perforation diameter, but in different lengths (d) Three sizes of tube, with different perforation diameters but the same annulus.

(a) and (b) above burn non-erosively and their two shapes should follow the same law of burning. They serve as a standard of comparison for the remaining shapes, so that the extent of erosive burning may be assessed. With samples (c) the dependence of erosive burning on the ratio (stick length)/(perforation diameter) for a particular perforation diameter, may be assessed. It is intended to fire different stick lengths of samples (d) viz. stick lengths of 1, 2, $3\frac{1}{2}$ and 5 ins, the last being the longest stick length which can be accommodated in the present design of Closed Vessel. Here, again, it will be possible to examine the effect of the (stick length)/(perforation diameter) ratio on erosive burning, but in this case there is the additional variant of perforation size which is thought to have an important bearing on ignition and erosive burning.

It is intended to fire the above samples in the Closed Vessel at two charge temperatures, viz. 35°F and 80°F, in order to obtain a better understanding of the quantitative effect of charge temperature on erosive burning. Most of the firings have, in fact, already been carried out, but the analysis of results has not yet proceeded far enough for any conclusions to be drawn. In the case of the M.T. samples, there was a very marked increase in erosive burning as the stick length was increased.

In connection with the above investigation, the manufacture of further M.T. samples of the same composition has been arranged. In this case, the variant is the perforation diameter, the ratio (Stick length)/(perforation diameter) being constant.

The M.T. shape of propellant is usually so dimensioned that, initially, the perforations account for about 40% of the total surface area of the grain. On the other hand, the corresponding figure for the tubular shape is only 25%. Thus, in this respect, tube is the better shape, but this advantage of a smaller proportion of internal burning surface is lost, in practice, by the use of larger stick-lengths. In the experiments outlined above, it will, of course, be possible to make a direct comparison of these two propellant shapes from the standpoint of their susceptibility to erosive burning.

In connection with the problem of developing satisfactory methods for igniting granular propellant charges in the gun, samples of two of the series I (i.e. picrite + D.G.N.) compositions, with flame temperatures of 2200° and 1700°K, have been manufactured in the M.T. form with unconventional dimensions. One of the 1700°K M.T. samples has a length/perforation diameter ratio of 27.5, which is close to the normal figure of about 25.

The second M.T. sample of this composition has a perforation diameter about five times that of the first and the grain is about twice as long, so that the length/perforation diameter in this case is approximately twelve. These two samples are ballistically equivalent. A third sample of this composition in M.T. form made for Closed Vessel firings only, has approximately the same web thickness and perforation diameter as the second, but is twice as long, the length to perforation diameter in this case being the normal figure of about 25. One sample of the 2200°K composition, in M.T. form, has a length to perforatic diameter ratio of 25. The second sample of this composition is in the form of chopped tube, with the length to perforation diameter ratio the same as for the M.T. sample. The third sample, also tubular in shape and with the same internal and external diameter as the second, was supplied in 6-inch lengths for Closed Vessel firings so that charges with different ratios of stick length to hole diameter may be fired. It is proposed to fire all of these special samples in the Closed Vessel, as well as in the gun, in the hope that it may be possible to obtain some qualitative correlation between phenomena disclosed by the Closed Vessel technique, and factors which have a disturbing influence in the propellant ignition and burning in the gun.

(7) Bibliography

(i) H.H.M. Pike. "The conversion of data from Closed Vessel firings for use in simplified ballistic calculations". A.R.D./Ballistics Report 64/42, A.C.2874/IB.137)

(ii) Prof. J.E. Lennard-Jones and J. Corner "The burning of a propellant and the effect of gas flow over its surface". A.C. 1173 I.B.19, Sept. 1941.

Note:- Reports with A.C. numbers are issued by the Secretary, Scientific Advisory Council, Ministry of Supply, Ivybridge House, Strand, London, W.C. 2.

APPENDIX A

Propellant Data

(a) Series I Cool Propellants

Composition No.	F.487/44	F.487/45	F.487/46	F.487/47
Composition:-				
Picrite	60	60	60	60
Guncotton	20	20	20	20
D.G.N.	17.36	14.22	11.16	7.90
D.B.P.	-	3.14	6.20	9.46
Carbamite	2.64	2.64	2.64	2.64
T_o - °K	2449	2200	1957	1693
λ_o - tons per sq.in./gms per c.c.	62.5	58.0	53.3	47.6
η - c.c.s. per gm	1.000	1.03	1.06	1.09
γ	1.265	1.280	1.295	1.312
Dimensions:-				
(i) Samples processed with Acetone/Alcohol Solvent				
Slotted tube				
Lot No. ARD	2079 A	2080 A	2081 A	2082 A
Finished size (ins)	.155-.054	.1515-.0515	.150-.051	.1485-.0495
Mean annulus (ins)	.0505	.0500	.0495	.0495
Annulus variation (ins)	.048-.054	.047-.053	.047-.054	.0465-.053
Wt.per 100" (grains)	599	583	567	559
Density (gms/c.c.)	1.632	1.620	1.602	1.581
Breaking diameter ratio	13.5	15	15.5	17.5
V.M. (per cent)	0.10	0.10	0.09	0.10
Multitube				
Lot No. A.R.D.	2079 B	2080 B	2081 B	2082 B
Finished size (ins)	.2665-.0235	.2625-.0230	.2660-.0235	.2630-.0255
Mean web (ins)	.049	.0485	.049	.0465
80% web limits (ins)	.047-.0505	.046-.051	.046-.052	.044-.0495
Mean outer web (ins)	.0495	.0485	.050	.048
Mean inner web (ins)	.0485	.048	.0475	.045
Mean outer hole	.0235	.023	.0235	.0245
Mean inner hole.	.0235	.023	.0235	.028
Density (gms/c.c)	1.637	1.620	1.602	1.580
Granules per lb.	488	523	553	562
V.M. (per cent)	0.10	0.10	0.09	0.11

(ii) Samples processed with Acetone/Water solvent

Composition No.	F.487/44	F.487/47
Slotted tube		
Lot No. A.R.D.	2092 A	2093 A
Finished size (ins)	.151-.053	.148-.050
Mean Annulus (ins)	.049	.049
Annulus variation (ins)	.047-.052	.046-.052
Wt. per 100" (grains)	591	569
Density (gms/c.c)	1.643	1.582
Breaking diameter ratio	24.5	20.5
V.M. (per cent)	0.05	0.07
Multitube		
Lot No. A.R.D.	2092 B.	2093 B
Finished size (ins)	.268-.026	.269-.0265
Mean web (ins)	.0475	.0475
80% web limits (ins)	.045-.050	.045-.050
Mean outer web (ins)	.0485	.0485
Mean inner web (ins)	.046	.046
Mean outer hole (ins)	.0255	.026
Mean inner hole (ins)	.0275	.028
Density (gms/c.c.)	1.641	1.581
Granules per lb.	511	530
V.M. (per cent)	0.10	0.11

(b) Series I.A. Cool Propellants

Composition No.	F.527/153	F.527/154	F.527/155	F.527/156
Composition:-				
Picrite	60	60	60	60
Guncotton (13.2%N, C.W.)	20	20	20	20
N.G.	13.72	11.33	8.86	6.38
D.B.P.	3.64	6.03	8.50	10.98
Carbamite	2.64	2.64	2.64	2.64
T_o - °K	2449	2206	1950	1710
λ_o - tons per sq.in./gms per c.c	62.2	57.9	52.9	47.9
η - c.c.s per gm.	1.00	1.03	1.06	1.10
γ	1.28	1.29	1.31	1.32
Dimensions :-				
Slotted tube				
Lot. No. A.R.D.	2408 B	2409 B	2410 B	2411 B.
Finished size (ins)	.1445-.044	.147-.042	.1465-.0445	.152-.0465
Mean annulus (ins)	.050	.0525	.051	.0525
80% annuli limits(ins)	.048-.053	.049-.046	.048-.053	.048-.055
Density (gms/c.c)	1.652	1.631	1.610	1.585
Wt. per 100" (grains)	591	613	607	597
V.M. (per cent)	0.08	0.08	0.08	0.08
Multitube				
Lot No. A.R.D.	2408 A	1409 A	2410 A	2411 A
Finished size (ins)	.265-.026	.2695-.0265	.270-.026	.270-.026
Mean web (ins)	.0465	.0475	.048	.048
80% web limits(ins)	.043-.050	.044-.0505	.046-.052	.045-.051
Mean outer web(ins)	.049	.0465	.049	.0495
Mean inner web (ins)	.0445	.048	.047	.0465
Mean outer hole (ins)	.025	.0265	.0255	.0255
Mean inner hole (ins)	.028	.027	.0275	.027
Density (gms/cc)	1.648	1.627	1.609	1.587
Granules per lb.	1320	1345	1340	1335
Cut length (ins)	0.615	0.615	0.615	0.62
V.M. (per cent)	0.10	0.08	0.10	0.08

Note the above lots were prepared from normal Naval grade picrite, of measured specific surface 20,000 sq.cms./c.c.

(c) Series I.B. Cool Propellants

Composition No.	F.428/178	F.428/179	F.428/180	F.426/181
Composition:-				
Guncotton (13.2%N, C.W.)	65	65	65	65
N.G.	20.2	17.9	15.4	13.1
D.B.P.	12.8	15.1	17.6	19.9.
Carbamite	2	2	2	2
T_δ - °K	2462	2221	1961	1722
λ_o - tons per sq.in/gms per cc.	61.2	57.0	52.0	47.1
η - c.c.s. per gram	1.015	1.04	1.080	1.097
γ	1.278	1.290	1.308	1.321
Dimensions:-				
Cord shape				
Lot No: A.R.D.	2460	2461	2462	2463
Finished size (ins)	.0520	.0523	.0508	.0510
80% diameter limits (ins)	.0510-.0526	.0510-.0527	.0500-.0513	.0497-.0511
Wt. per 100" (grains)	82.5	82.6	77.0	76.8
Density (gms/c.c.)	1.538	1.518	1.500	1.486
Breaking diameter ratio	6	6	6	

(d)Series I.C. Cool Propellants

Composition No.	F.487/66	F487/67	F487/68	F487/69
Composition:-				
Guncotton(13.2% N)	70	70	70	70
D.G.N.	20.2	17.3	14.3	11.4
D.B.P.	7.8	10.7	13.7	16.6
Carbamite	2	2	2	2
V.M.(per cent)	0.06	0.08	0.15	0.13
T_o - °K	2465	2227	1966	1729
λ_o - tons per sq.in/gm.per c.c.	61.4	57.2	52.3	47.5
η - c.c.s. per m.	1.011	1.035	1.060	1.091
γ	1.276	1.289	1.303	1.319
Dimensions:-				
Cord shape				
Lot No. C.R.D.D.	2604	2605	2606	2607
Finished size (ins)	0.050	0.051	0.050	0.052
Wt. per 100" (grains).	76.0	76.6	74.5	79.9
Density (gms)/cc.)	1.536	1.514	1.496	1.483

D.G.N. = Diethylene glycol Dinitrate
D.B.P. = Dibutylphthalate
N.G. = Nitroglycerine
V.M. = Volatile material
T_o = Propellant adiabatic flame temperature
λ_o = Propellant force constant, calculated from nominal composition and thermochemical data
η = Co-volume of propellant gases
γ = Ratio of specific heats of the propellant gases.

Appendix B

The original manufacture of the four series of cool propellants was in small quantities only, for Closed Vessel testing, and was carried out on the small scale plant at E.R.D.E. Woolwich, Manufacture on a large scale, for gun trials, has had to be carried out on plant of higher capacity, because of the quantities involved. It is well known that differences in propellant burning can occur between the products of different factories producing the same nominal composition, and such differences, therefore, may give rise to misleading results when propellants made at different factories are compared. Keeping this in mind, the rate of burning of the E.R.D.E. sample of composition F.428/180 was compared with the rates of burning of two samples of the same composition manufactured at Waltham Abbey, lots WACX. 186A and B. The E.R.D.E. sample was in cord form, and the Waltham Abbey samples were both in tubular form. In Fig. 11, the ratios of the rates of burning of the W.A.C.X. lots to the rate of burning of the E.R.D.E. lot are plotted against the amount of charge burnt. From Fig. 11, it is seen that, as in the case of the M.T. samples of series I and I.A compositions, there is an appreciable time lag before ignition is completed in the perforation of the tubular shape. This is shown by the shapes of the curves in the early stages of burning, the plotted ratios reaching unity only after, an appreciable amount of charge has burned away.

The hole diameters for WACX 186A and B were 0.0187 in. and 0.0207 in. respectively. As the same stick length of 5-in. was used in both cases, the ratios of stick length to perforation diameter were 267 and 241 respectively. From Fig 11 it is seen that the lot with the larger perforation diameter i.e. WACX 186 B, burns at about the same rate as the E.R.D.E. cord sample over a large part of the burning range. Shortly after the completion of ignition in the perforation of lot WACX 186A, the rate of burning of this sample reached a value nearly 10% greater than the E.R.D.E. cord sample, but as burning continued this difference decreased until the rates of burning were the same at about 65% burnt. From the shape of the curve, it is probable that this difference in burning rates is due to erosive burning of the tubular sample. Thus, erosive burning occurred only in the case of the sample with the larger ratio of stick length to hole diameter. There is further confirmation of this in Fig. 11, burning - through of the annulus, as shown by the decreasing ratio of rates of burning, occurring first in the case of the sample with the smaller perforation diameter.

Erosive burning has the effect of altering the constants α and β in the burning law - Rate of burning $= \beta P^{\alpha}$. The actual values of α and β in the present instance were:-

Lot No.	β	α
WACX 186A	0.602	0.891
WACX 186B	0.500	0.966

These two laws cross at about 12 tons per sq.in. pressure. This is very nearly the same pressure at which either law will intersect the equivalent linear law corresponding to gun conditions. Thus, the values of for the two samples would be expected to be very nearly equal. The calculated values were, in fact, 0.462 and 0.461 for WACX 186A and B respectively. The figure for the E.R.D.E. lot, of cord shape, was 0.467.

Two samples of composition F.487/68, in tube form, were manufactured at Waltham Abbey for gun trials. These two samples were of different size, lot WACX. 181 having a perforation diameter of 0.0345 in., and lot WACX 182 a perforation diameter of 0.048 in. These lots also were fired in the Closed Vessel, the charge length being 5-ins, as before. Thus, the ratio of stick length to hole diameter was 145 in the first case, and 104 in the second.

The ratio of rate of burning of lot WACX 181 to the rate of burning of the E.R.D.E. cord sample is plotted against the amount of charge burnt in Fig.12. It is seen that as in previous examples of perforated propellant, there is a considerable delay before ignition in the hole is completed. In the present case, very shortly after this stage was reached the rate of burning of the tubular sample reached a value about 13% greater than that of the cord. This peak value, however, soon commenced to fall until, at about 65% burnt, the tube burned at the same rate as the cord. Beyond this stage, the ratio of rates of burning continued to decrease, indicating that the erosive burning present in the early stages had changed the geometry of the propellant sticks in such a manner that they were now burning through in places while there was still an appreciable annular thickness at other points.

In comparison with a propellant shape which burns non-erosively, erosive burning of the perforated shape is equivalent, in effect, to a change in form function θ, the constant term in the expression:-

$$\text{Fraction of charge burnt} = (1-f)(1+\theta f)$$

where f is the remaining fraction of the smallest dimension of the propellant at any stage during burning. If θ is positive in sign, it follows that the charge area decreases as burning proceeds. Ignoring the small area of the sticks, and assuming parallel-layer burning, the surface area of tubular propellant is constant as burning proceeds, and $\theta = 0$.

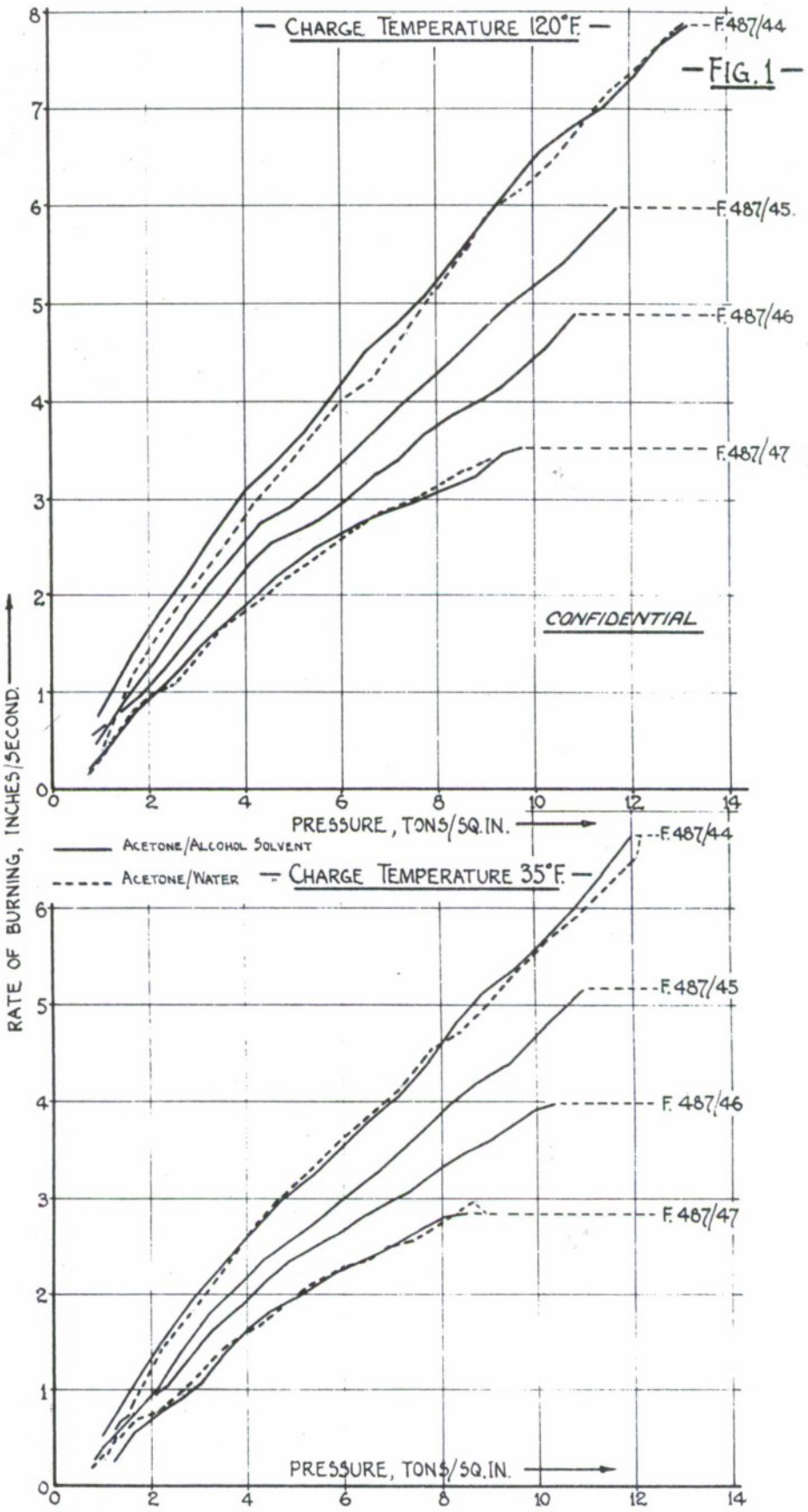
Erosive burning is equivalent to a fictitious increase in charge area during the early stages of burning. However, as the charge burns away, erosive burning decreases as the perforation diameter becomes larger, i.e. the fictitious burning surface decreases also. Thus, the variation of erosive burning with the amount of charge burnt is similar, qualitatively, to a change of θ with parallel-layer burning.

In the case of lot WACX.181, the use of $\theta = 0.2$ instead of $\theta = 0$ in the Closed Vessel analysis leads to better agreement between the rate of burning of the tubular sample and the rate of burning of the E.R.D.E. cord sample, as shown by the dotted curve of Fig.12. (Actually, the agreement would be a little better if θ were a little less than 0.2). Thus, the law of burning for the E.R.D.E. cord sample would agree very closely with that for the WACX.181 tube, using $\theta = 0.2$ for the tube. Using the true geometrical form function, however, the burning laws were:-

For the E.R.D.E. cord, rate of burning = $0.487\ P^{1.003}$ $\left(\beta_1\,(_{24}) = 0.476\right)$
For the WACX 181 tube, rate of burning = $0.609\ P^{0.916}$ $\left(\beta_1\,(_{24}) = 0.499\right)$

The second sample of F.487/68 manufactured at Waltham Abbey (lot WACX 182) had a larger perforation diameter than the first: the stick length, as fired, being the same in the two cases, the gas velocity in the perforation, for the same pressure, would be lower in this case than in the previous one, and this would be expected to cause less erosive burning than before. It can be seen from Fig.10, in which the ratio of the rate of burning of lot WACX.182 to the rate of burning of the E.R.D.E. cord sample is plotted against the amount of charge burnt, that there was, in fact, very little erosive burning in this case. The striking differences between figs. 10 and 12 are in the peak values of the plotted ratios, and in the rates at which the ratios decrease in the later stages of burning. When 80% of the charge is burnt, lot WACX 181 is apparently burning at a rate of only 86% that of the cord, but the corresponding figure for lot WACX.182 is nearly 93%. The adoption of $\theta = 0.05$ for lot WACX 182 brings the index α in the burning law for this lot into better agreement with that for cord, but β for the tube is lower than for the cord sample. For $\theta = 0$, $\alpha = .988$ and $\beta = 0.496$ for WACX 182, and $\beta_1(_{24}) = 0.481$. Thus, if these figures are compared with those for WACX.181 and the E.R.D.E cord sample, it is seen that, as in the case of F.428/180. β and $\beta_1(_{24})$ decrease, and α increases, and tends to approach the values for the cord sample, as erosive burning is reduced from one sample to another.

A sample of F.487/46 (lot WACX.169) manufactured in slotted tube form at Waltham Abbey was found to be slower burning than the original sample made at E.R.D.E.Woolwich (lot ERD.2079 A). The WAC lot burned according to the law $0.707\ P^{0.721}$, whereas the law for the E.R.D. lot was $0.720\ P^{0.764}$. The corresponding values of $\beta_1(_{24})$ were, respectively, 0.393 and 0.354. The value of λ_0 for the WAC sample, determined experimentally, was about $2\frac{1}{2}$ % smaller than the calculated value, whereas with the E.R.D. sample the difference was of opposite sign and about half this magnitude.



—FIG. 1—

RATES OF BURNING OF SERIES I. COOL PROPELLANTS. (SLOTTED TUBE)

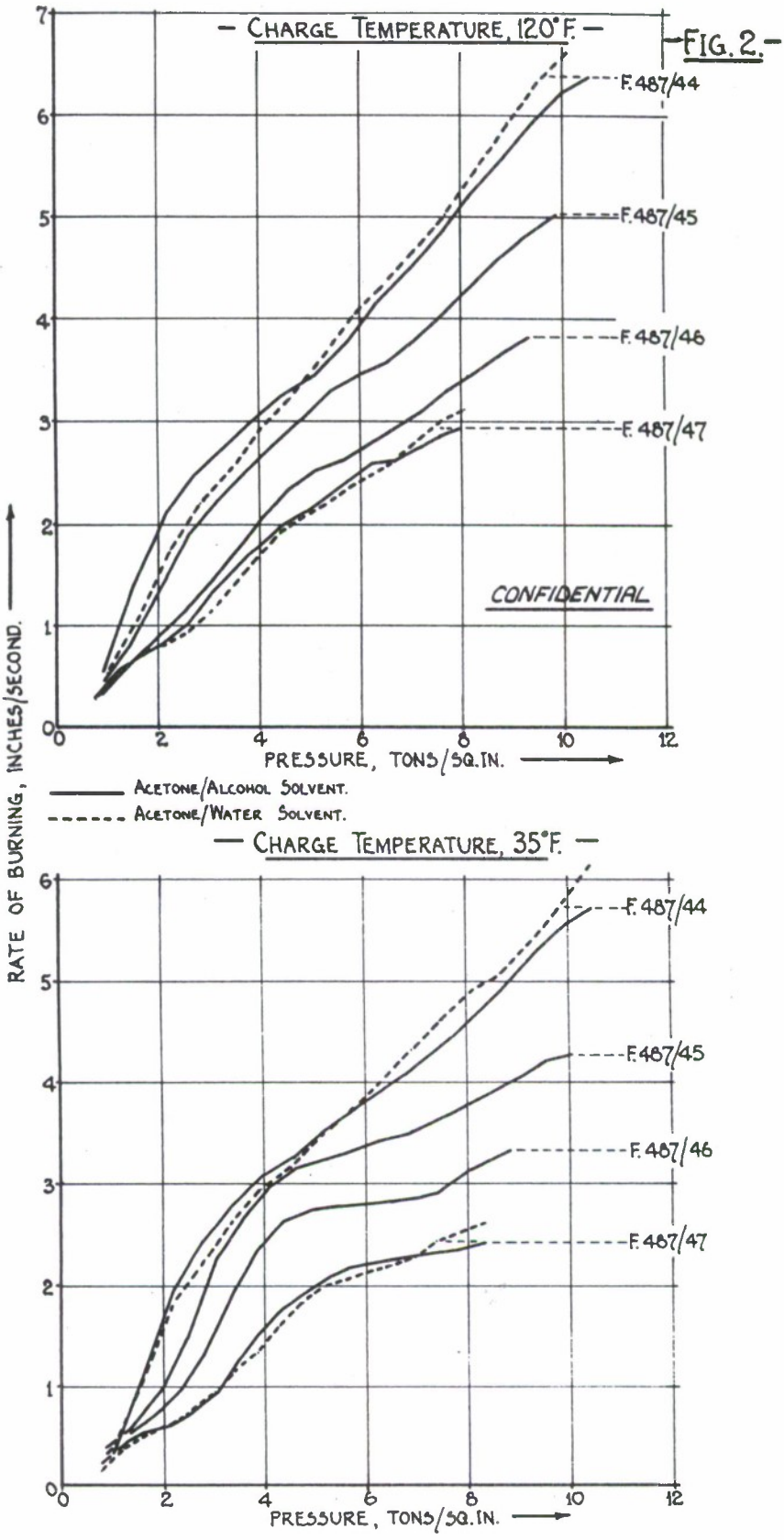
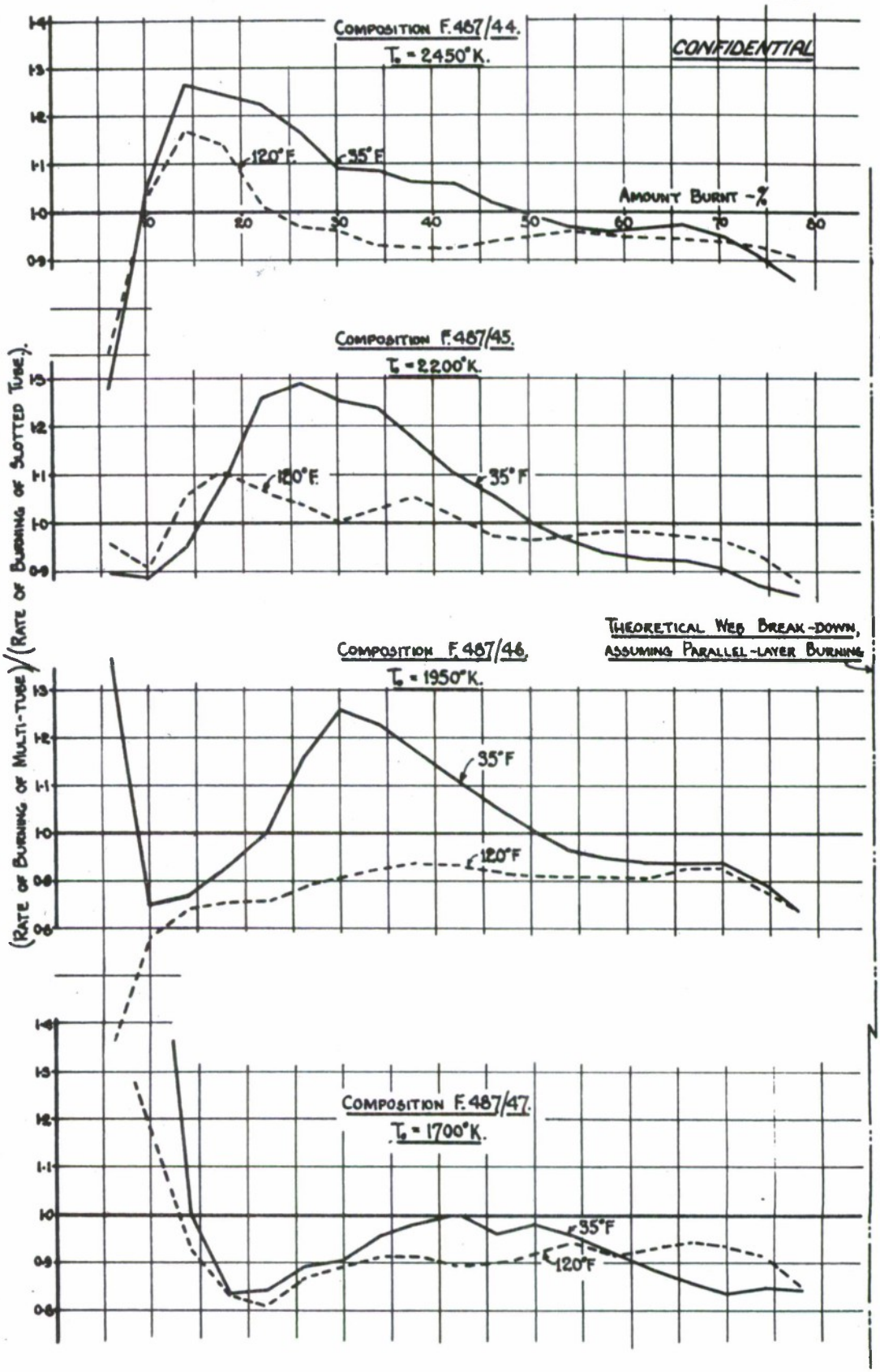


FIG. 2.-

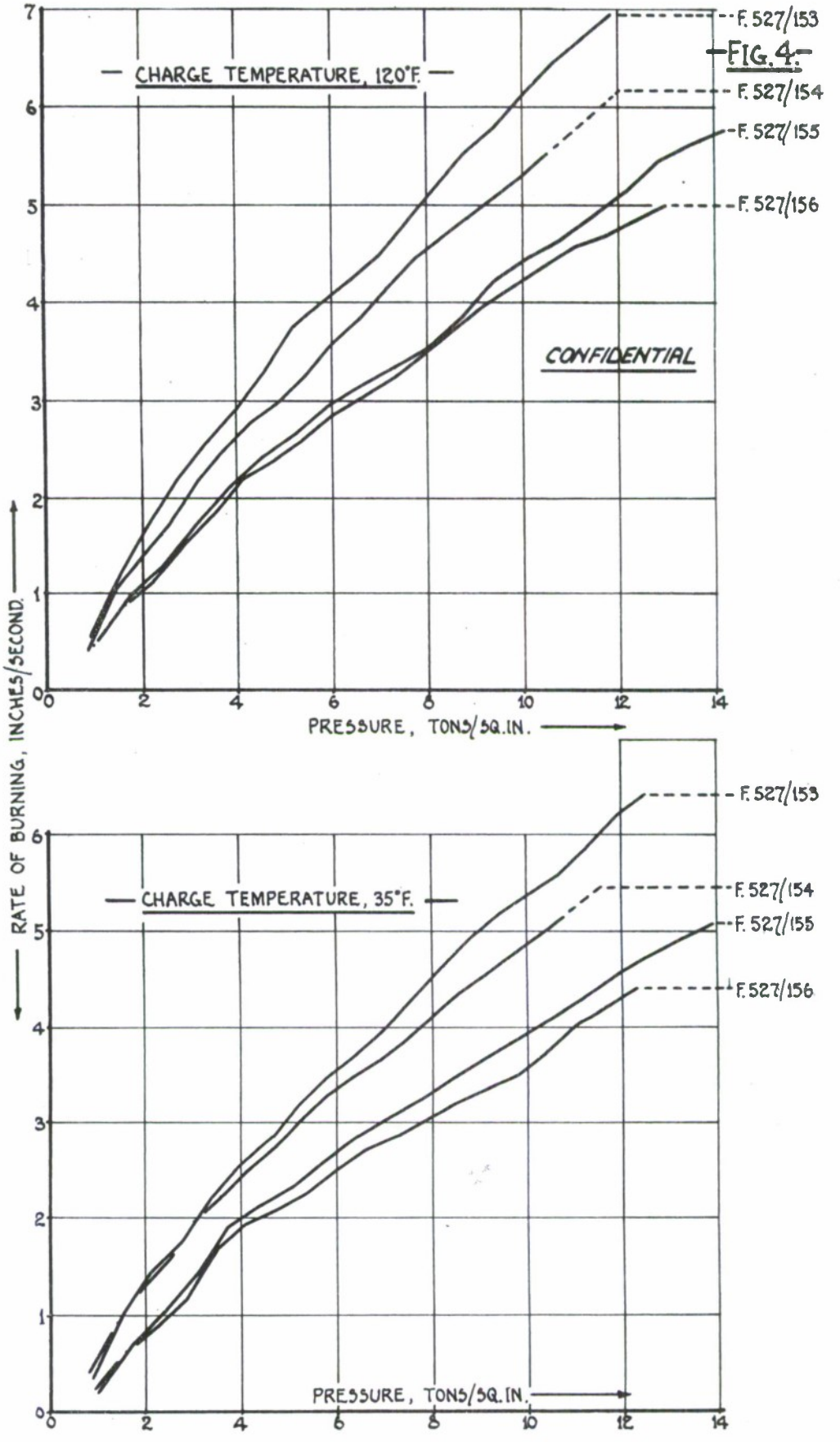
— RATES OF BURNING OF SERIES. I. COOL PROPELLANTS. —

— PROPELLANT SHAPE:- MULTI-TUBE. —

-FIG. 3.-



— SERIES. I. COOL PROPELLANTS. —



— RATES OF BURNING OF SERIES IA. COOL PROPELLANTS. (SLOTTED TUBE). —

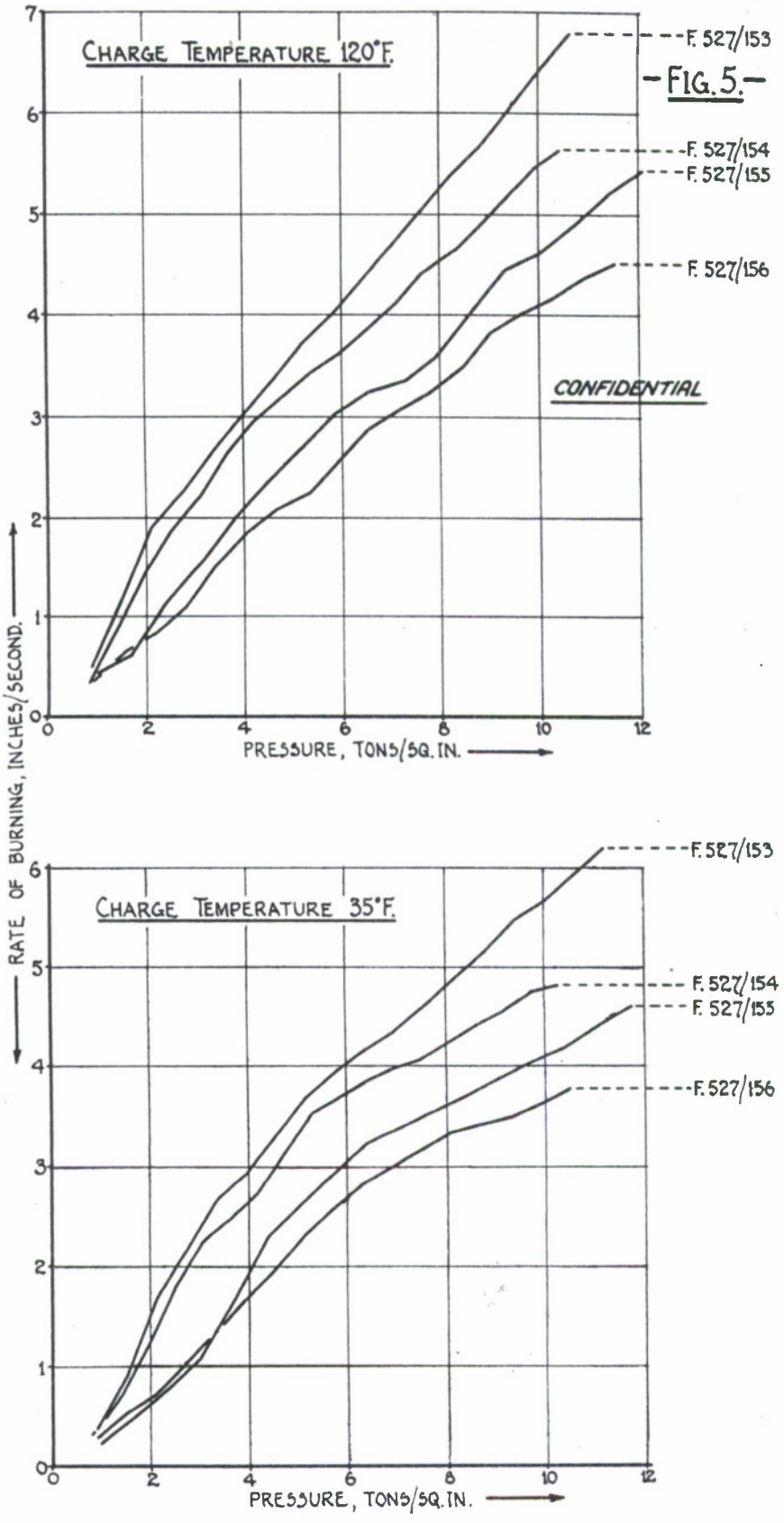
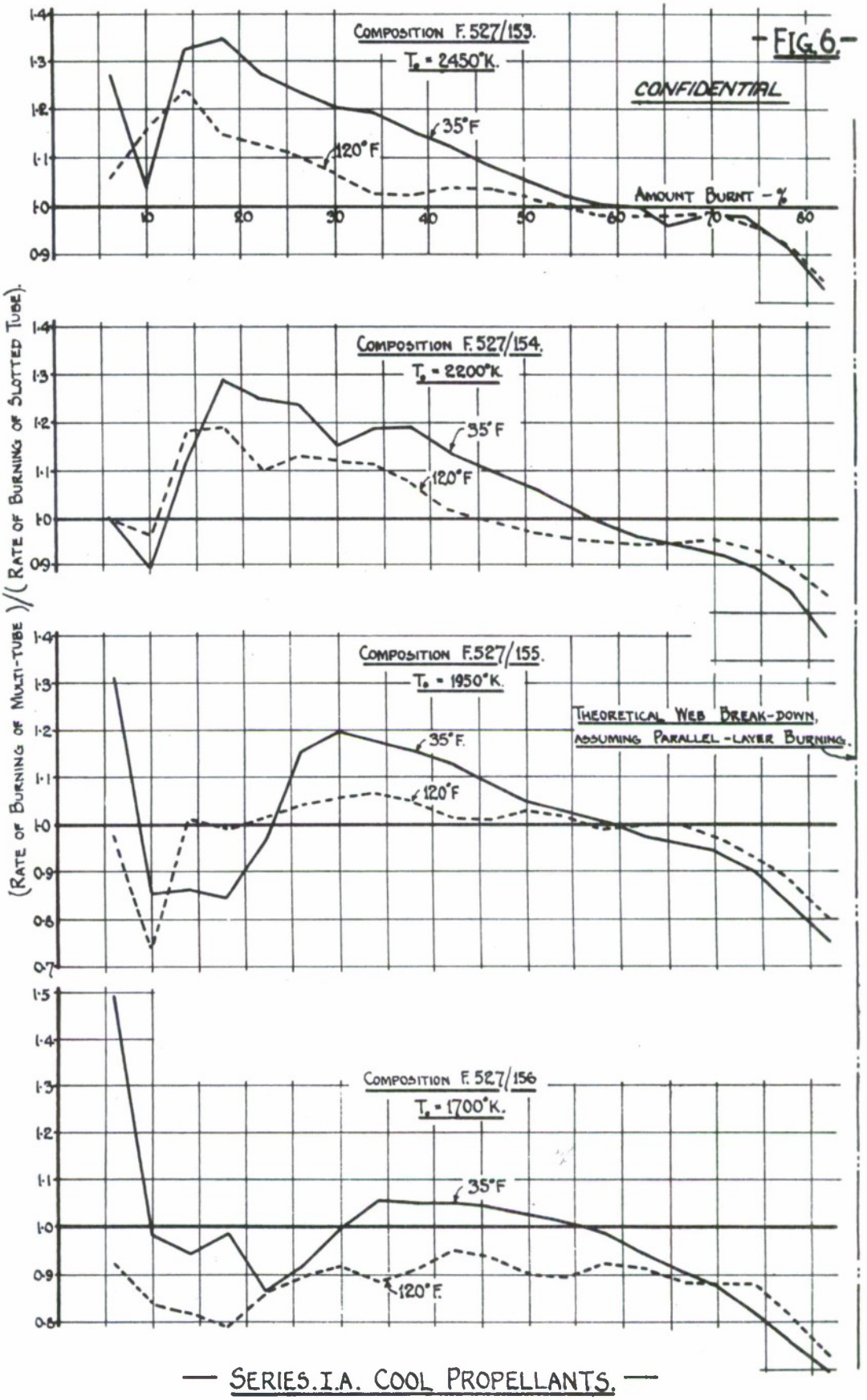


FIG. 5.

— RATES OF BURNING OF SERIES IA. COOL PROPELLANTS. —

PROPELLANT SHAPE :- MULTI-TUBE.



— SERIES I.A. COOL PROPELLANTS. —

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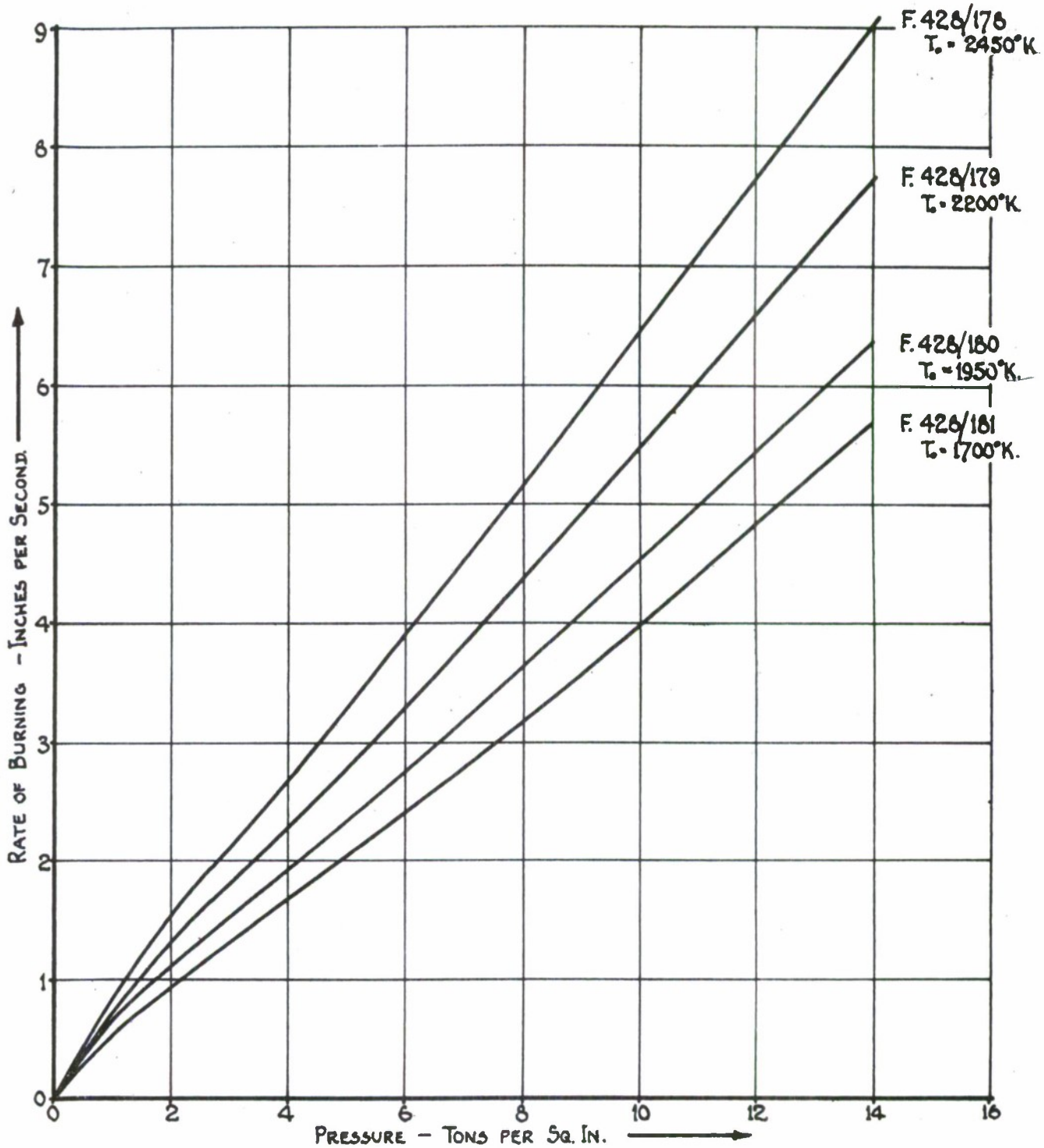

— SERIES. I.B. COOL PROPELLANTS. —

SHAPE :- CORD.

CHARGE TEMPERATURE :- 80°F.

— FIG. 8. —

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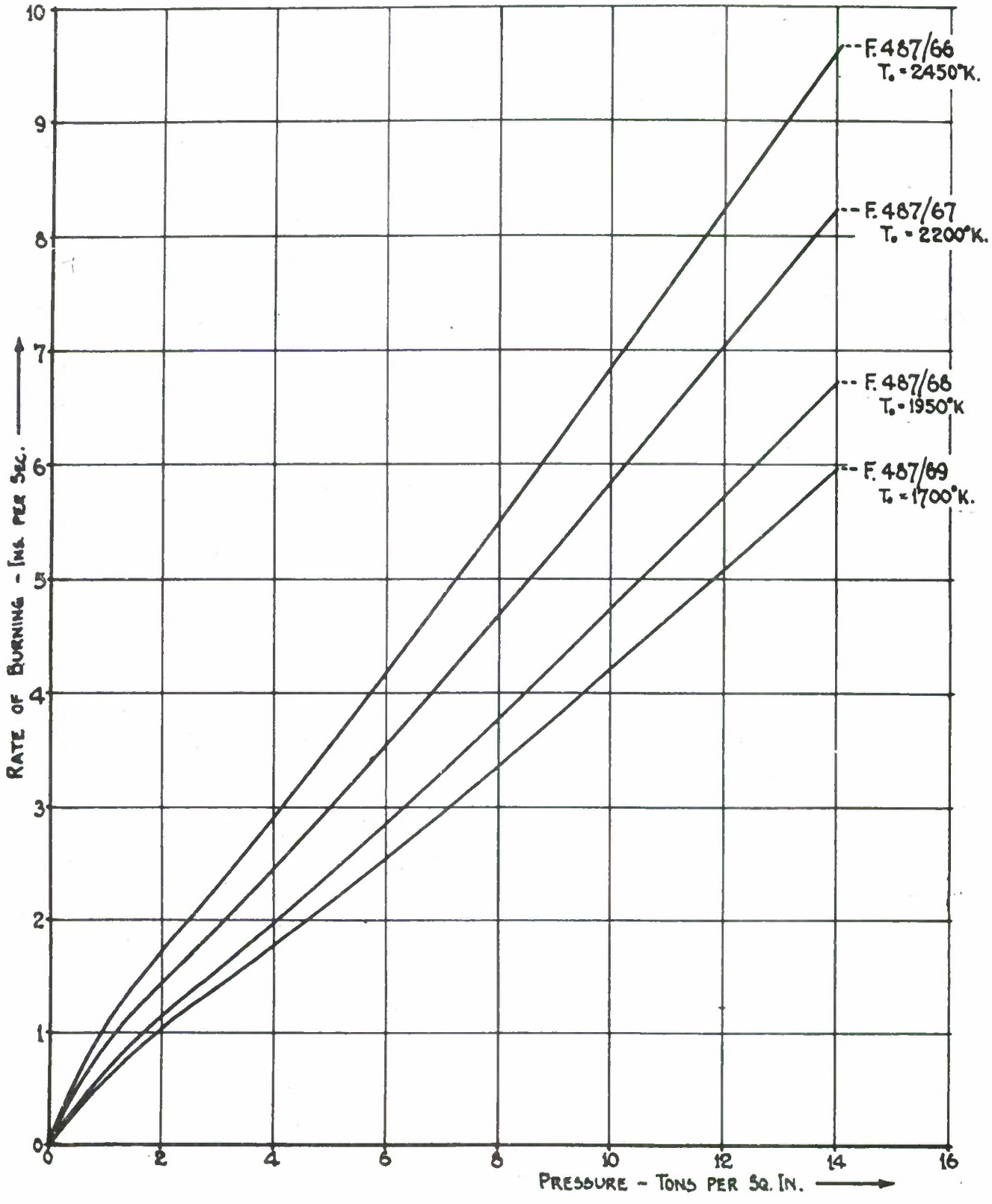

— SERIES. I.C. COOL PROPELLANTS. —

SHAPE :- CORD.

CHARGE TEMPERATURE :- 80°F

- FIG. 9. -

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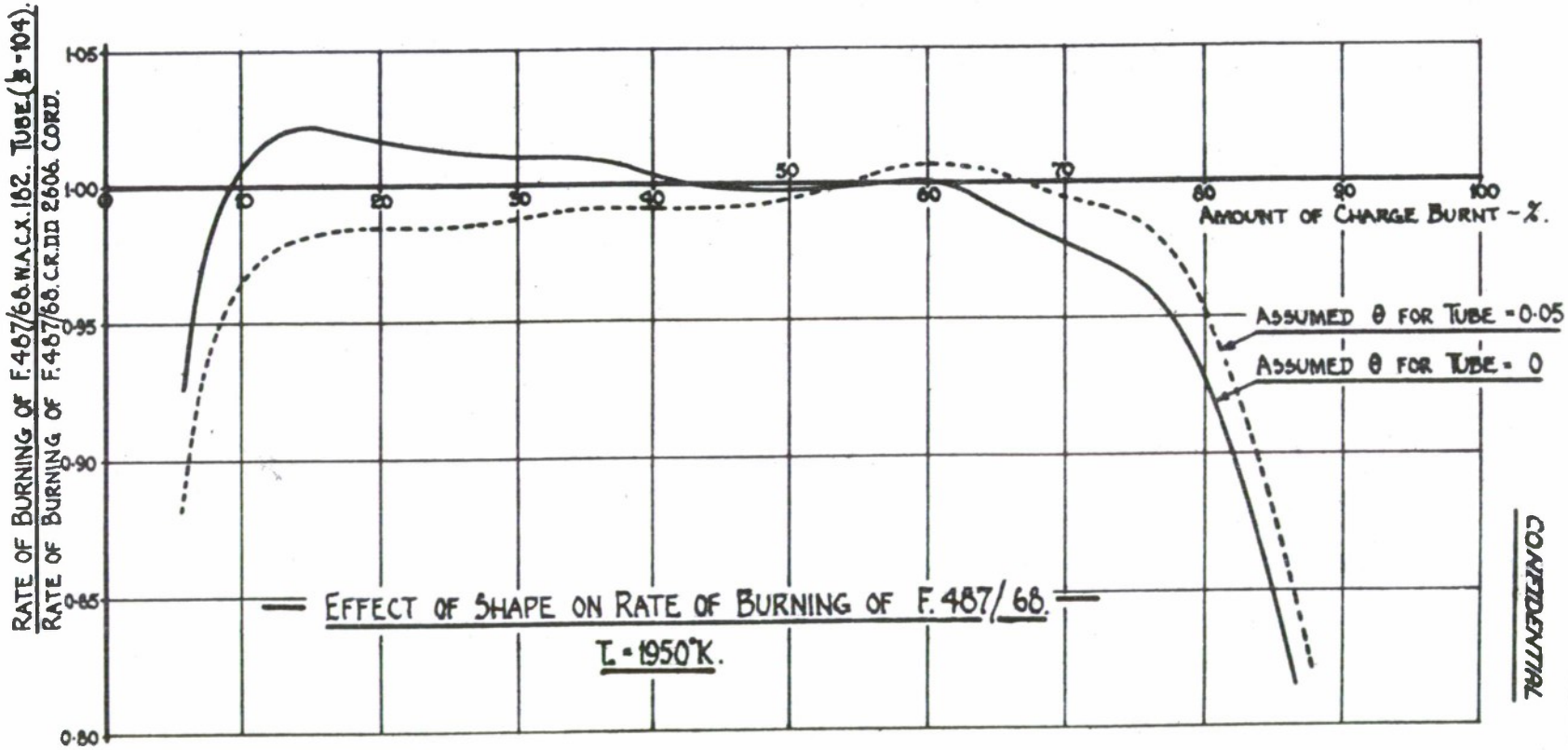

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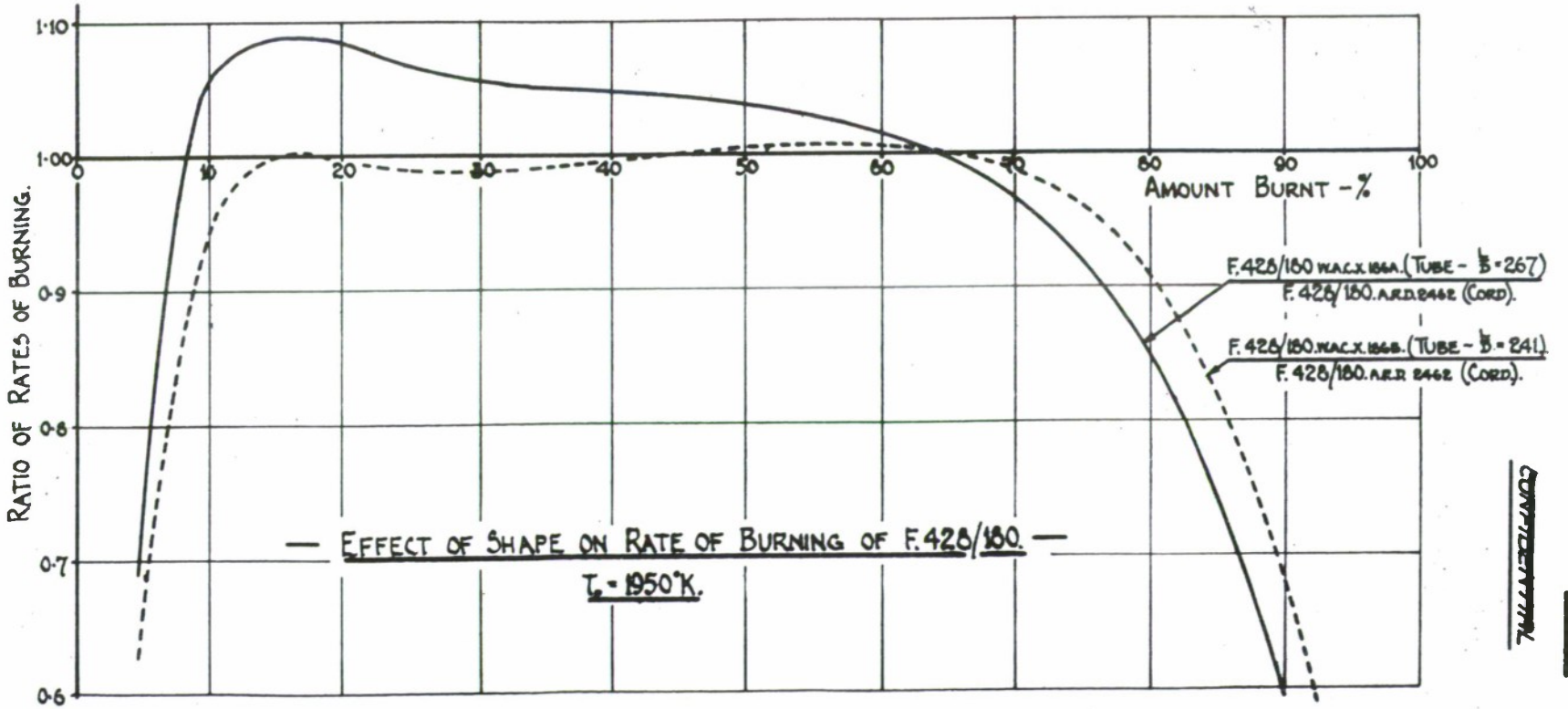
— Fig. 10. —



— EFFECT OF SHAPE ON RATE OF BURNING OF F.428/180. —

T_o = 1950°K.

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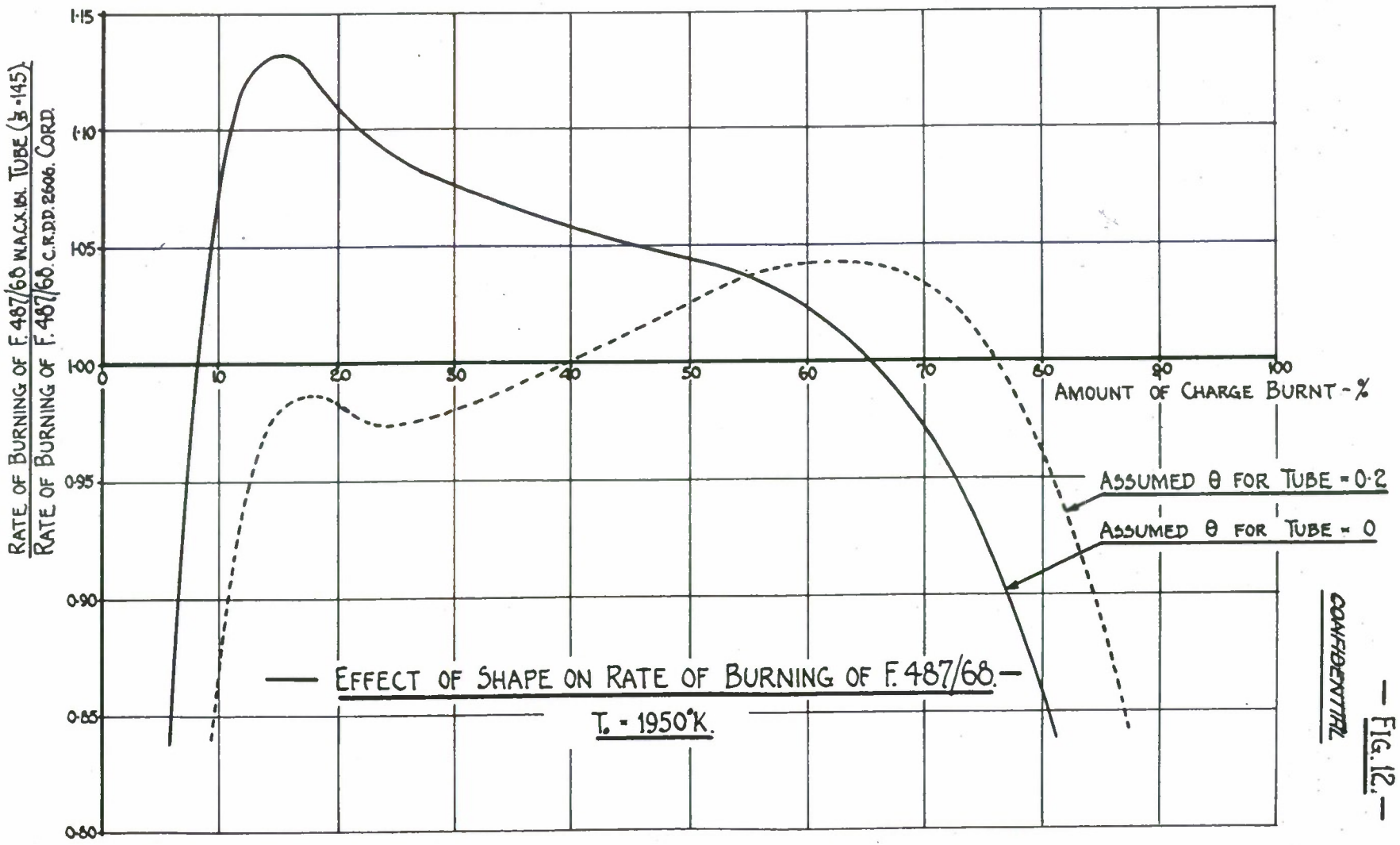
— FIG. 11. —



— FIG. 12. —

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